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Assessment of a pilot solar V-trough reactor for solar water disinfection

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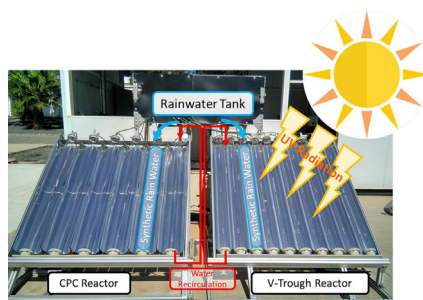
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HIGHLIGHTS

- A new mirror configuration design (V-trough) was tested and set against common CPC.
- V-trough reactor is better suited to solar inactivation than CPC reactor.
- An increment of treated water over 100 L per day was accomplished.
- Four bacteria commonly found in HRW were photo-inactivated simultaneously.
- Solar resistance decreased as *E. faecalis* > *E. coli* > *S. enteritidis* > *P. aeruginosa*.

GRAPHICAL ABSTRACT



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ABSTRACT

Rural and isolated communities of low-income countries suffer the lack of access to safe drinking water. Harvested rainwater (HRW) is becoming an alternative source of freshwater in many areas of the world. Nevertheless, its quality usually doesn't meet drinking water standards, posing a health risk for human consumption. Solar water disinfection – SODIS – is a low-cost household intervention used to disinfect water. In this work, we investigate a new solar photoreactor based on V-trough mirrors as alternative to the most used Compound Parabolic Collector (CPC) geometry at pilot scale (54 and 32 L per batch), with the aim of reducing costs and reactor surface's footprint. An experimental assessment of two key parameters as water recirculation and mirror geometry was carried out. For this study several water-pathogens commonly found in HRW were used, *Escherichia coli*, *Enterococcus faecalis*, *Salmonella enteritidis* and *Pseudomonas aeruginosa*. Best results were obtained with the V-trough reactor in static condition, where > 5-LRV (log-reduction value) for all bacteria tested were reached with a solar-UVA dose of 254 kJ m^{-2} (90 min). At this operational condition, a total volume of 162 L (3 batches) of water were treated in one full sunny day in Spain (300 min of effective treatment time). A comparison between CPC and V-trough mirrors resulted in similar disinfection efficiencies even if the actinometric results showed that CPC collects 1.58 times more photon flux than the V-trough in the solar-UVA region. These results show the great performance of the V-trough mirror for this application, which is cheaper to produce than CPC and permits treating higher amounts (66% more) of water for the same collector area and same treatment time.

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1. Introduction

Fresh safe water is a limited natural resource essential to humans. In 2015 the United Nations and all its State Members adopted the Sustainable Developments Goals (SDGs), among them, the SDG6 aims at ensuring availability and sustainable management of water and sanitation for all by 2030 [1]. The World Health Organisation (WHO) recognised that 1.8 billion people globally still use drinking water that is contaminated by faecal matter, with nearly 1,000 children dying each day due to preventable water and sanitation-related diarrhoeal diseases [2].

Harvested rainwater (HRW) has been recognised as an alternative and sustainable water source that could provide water directly to households [3,4]. HRW has successfully been used worldwide in a number of countries including Australia, Bermuda Islands, Greece, Jordan and South Africa [5]. Nevertheless, its quality depends on the presence of particulate, suspended and dissolved matter streamed by the rain proceeding from the roof, pipes and air. One of the main sources of contamination are the chemicals from the roof materials, commonly leaching lead and other heavy metals exceeding the WHO drinking water standards [6]. Moreover, the microbiological quality of HRW due to animal faecal bacteria and parasites is also of great concern. The most commonly found bacterial pathogens in rainwater include *Campylobacter* spp., *Salmonella* spp., *Shigella* spp., *Vibrio* spp., and other opportunistic bacterial and parasitic pathogens, *Aeromonas* spp., *Pseudomonas* spp., *Legionella* spp., *Mycobacterium* spp., *Cryptosporidium* spp. and *Giardia* spp. [6]. Many cases of illnesses associated with the use of roof-captured rainwater are reported elsewhere [7]. Natural disinfection processes can reduce faecal bacteria concentrations by 1 to 2 orders of magnitude or LRV (logarithmic reduction value) in 10–15 days within the storage tanks [8], which requires additional treatment to ensure drinking water quality. Due to the abundant number of bacteria and the seasonality of the microbial consortium, when monitoring rainwater microbial quality, only indicators as *E. coli*, total and faecal coliforms or enterococci are taken into account [9,10]. Therefore, the selection of specific waterborne pathogens might be of high interest for the application of HRW treatment.

The most commonly used disinfection methods in low-income countries are filtration and chlorination, although solar water disinfection (SODIS) is also an alternative. It is a zero-cost, easy-to-use and suitable household water treatment based on solar inactivation of microbial pathogens. It was recommended by the WHO as a Household Water Treatment and Storage intervention when there are no other improved sources in place [11]. SODIS consists on exposing water contained in plastic bottles (usually 1.5–2 L Polyethylene Terephthalate - PET) to direct sunlight for 6 h on plain sun or 48 h on cloudy conditions. The efficiency of SODIS has been demonstrated for a wide range of microorganisms including bacteria (*E. coli*, *Enterococcus* sp., or *Salmonella* sp.), fungi (*Fusarium* sp. or *Candida albicans*, among others), viruses (Bacteriophage f2, Poliovirus, Rotavirus or Norovirus), protozoa (*Cryptosporidium parvum*, *Giardia*, or *Entamoeba*) and helminths (*Ascaris*) [11].

Several drawbacks related with SODIS application are still unsolved, being the major concerns, the limited efficacy and the small volume of water than can be treated. Recent researches are trying to overcome these limitations investigating different solutions based on the use of new UV-transparent materials and the design of new solar-engineered reactors to scale-up the process and improve the efficiency of the treatment. For example, Fisher and collaborators [12] studied the use of polypropylene copolymer (PPCO), PET, polystyrene (PS) or polycarbonate (PC) bottles for SODIS. These materials have a higher Ultraviolet A (UVA) and B (UVB)-transmission than PET, which allowed a quicker pathogens reduction [12]. Figueredo-Fernandez et al. [13] evaluated the use of PC and polyethylene (PE) bags for solar water disinfection, finding also a higher efficiency than with PET bottles. When large volume was a concern, an increment of the treated volume

was investigated for several authors. Keogh et al. [14] investigated the use of 19 L-PC bottles as SODIS containers finding no significant difference in the inactivation profiles for *E. coli* in clear water between 1.5 L-PET bottles and 19 L-PC containers. The use of solar Compound Parabolic Collectors (CPC) to increase the solar input has been also investigated and proven successful for the solar inactivation of a wide variety of waterborne pathogens [11,15–19]. The use of CPC reduces solar treatment time and increases the volume of treated water [20]. Nevertheless, it is not easy to develop an efficient SODIS system at large scale for delivering enough amount of safe water. In this line, Ubomba-Jaswa et al. [17] investigated a solar CPC batch system made of methyl-methacrylate with a tube diameter of 200 mm to disinfect 25 L of well water contaminated with *E. coli*, producing a 6 LRV within 5 h (300 min) in transparent water (< 5 NTU) and 7 h (420 min) in turbid (100 NTU) water. Recently, Castro et al. [21] proposed a synergistic SODIS-thermal model that was validated for a number of SODIS containers materials (PET, PC, borosilicate glass, methacrylate) and reactors (CPC, bottles and tubes with diameters from 50 to 200 mm) under real conditions of sunlight and turbidity (5 to 300 NTU) for *E. coli* inactivation. According to this work, the most efficient systems use solar collectors, UV-transparent materials, clear water and large tube diameter values (> 100 mm) [21].

Scaling up these solar systems has become a significant issue, as UV absorption by water and reactor materials detracts the process, therefore some critical aspects like water path-length [21], turbidity, water flow [16] and dissolved oxygen [22] must be considered when designing large SODIS reactors. Moreover, other factors as the costs of the materials and manufacturing, built with resilient and available materials, easy-to-use and maintain, and efficient for several waterborne pathogens commonly found in HRW, might be addressed when the application is for harvested rainwater.

This work aimed at the investigation of a V-trough solar photo-reactor at pilot scale, 54 L. A comparison between V-trough and CPC collectors was experimentally carried out for solar water disinfection. The influence of the water recirculation was also investigated as a key design parameter. The V-trough reactor's efficiency was assessed for the inactivation of four different pathogens commonly found in HRW, *E. coli*, *E. faecalis*, *S. enteritidis* and *P. aeruginosa*. The total treatment capacity of the system was tested under natural sunlight by treating a number of consecutive batches of contaminated HRW.

2. Material and methods

2.1. CPC and V-trough reactor

Two new solar reactors have been designed and constructed by Ecosystem Environmental Services S.A, Barcelona, Spain (Fig. 1). One of them consists of 6 transparent tubes placed in the linear focus of 6 CPC anodized aluminium reflectors, so-called CPC-reactor (Fig. 1 (b)). The other is made of 10 tubes located in the linear focus of anodized aluminium flat V shaped reflectors, named V-trough reactor (Fig. 1 (c)). Both solar reactors are placed on a 37°-tilted (ensuring a maximum incidence of normal radiation) platform resistant to the outdoor conditions. The reactor tubes are commercial borosilicate Schott-Duran® (Germany), with UVA transmittance of 89–90%. Each reactor's tubes were parallel connected to the 92 L-tank (Fig. 1(c)). The bottom part of each photo-reactor was kept in darkness due to this configuration, with means a 6 and 7% of the volume is not illuminated (dead volume) in the CPC and V-trough reactors, respectively. The CPC and V-trough collectors made of anodised aluminium (Miro Sun®, Alanod, Germany), with a global UVA reflectivity of 95% [15]. The 92 L-tank (simulating a rainwater tank) was used to prepare and homogenise the water samples and gravity feed the reactors for each experiment. Each reactor module was equipped with a recirculation circuit, where a centrifugal pump (Panworld NH5PX-Z, 5 W) was connected via plastic tubes to the reactor glass tubes. The recirculation flow rate in each tube was 2 L

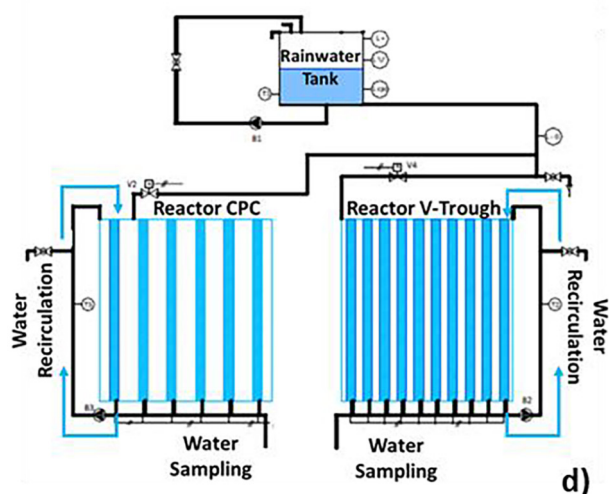
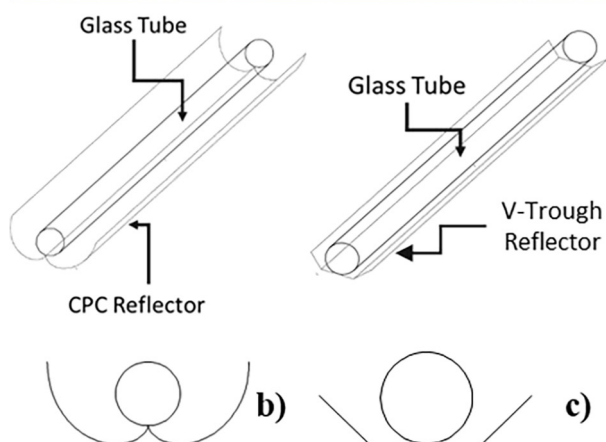
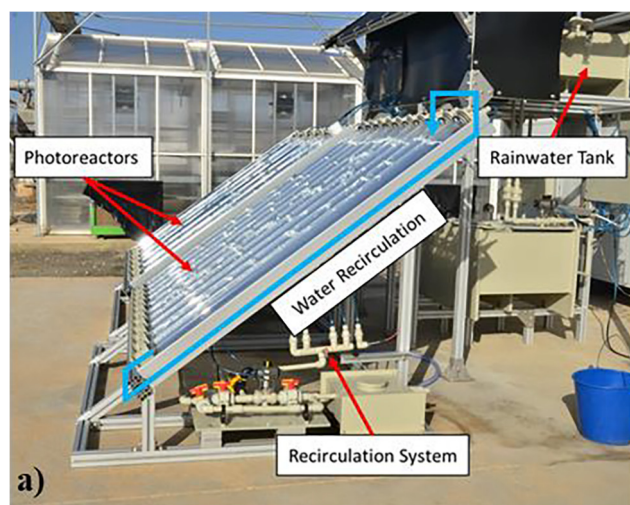


Fig. 1. Photograph of the new solar photo-reactors under evaluation (a) Diagram of the solar reflectors used, CPC-mirror (b) and V-trough mirror (c) Diagram of recirculation system (d).

min^{-1} in both modules. Water samples were taken from the sampling valves (Fig. 1(c)). The technical characteristics of each solar reactor are shown in Table 1.

2.2. Bacterial strain and quantification

Four collection-type bacterial strains were selected among the most frequently found in HRW, i.e. *Escherichia coli* K-12 (CECT 4624),

Table 1

Technical characteristics of solar photo-reactors tested.

	CPC-reactor	V-trough reactor
Total volume	32 L	54 L
Illuminated volume	30 L	50 L
Illuminated surface	2.04 m ²	1.98 m ²
External tube diameter	75 mm	75 mm
Number of tubes	6	10
Length of tube	1500 mm	1500 mm
Tube thickness	2.2 mm	2.2 mm
¹ Concentration Factor	1.04	0.56

¹ Concentration Factor (CF) = ratio of the area of aperture of the system to the area of the receiver; the aperture of the system is the projected area of the collector facing the sun.

Enterococcus faecalis (CECT 5143), *Salmonella enterica* subsp. *enterica* (Serovar Enteritidis) (CECT 4155) and *Pseudomonas aeruginosa* (CECT 110) (all of them are Gram-negative bacterium except for *E. faecalis* which is Gram-positive). Growth media Luria-Bertani Broth (Merck KGaA®, Darmstadt, Germany) was used for *E. coli* and *E. faecalis*, Tryptone Soya Broth (TSB) (Merck KGaA®, Darmstadt, Germany) for *S. enteritidis* and Nutrient Broth II (Merck KGaA®, Darmstadt, Germany) for *P. aeruginosa*. They were incubated at 37 °C in a rotatory shaker for 20 h and used in stationary phase for the stock suspension (10^9 CFU mL⁻¹). They were centrifuged at $900 \times g$ for 10 min. Bacterial pellets were re-suspended in phosphate buffered saline (PBS) (Sigma-Aldrich®, Germany). Each suspension was spiked in the reactor tank to get an initial (each strain) bacterial concentration of 10^6 CFU mL⁻¹. Water samples were serially diluted in PBS for plating and enumeration, using the corresponding selective media for each bacterium, ENDO Agar (Merck KGaA®, Darmstadt, Germany) for *E. coli*, Slanetz Bartley Agar (Scharlau®, Spain) for *E. faecalis*, Salmonella Shigella Agar (Scharlau®, Spain) for *S. enteritidis* and Pseudomonas Chromogenic agar (Condalab, Spain) for *P. aeruginosa*. For the lowest bacterial concentrations expected, 500 μL of samples were directly spread on the plates to reach a detection limit (DL) of 2 CFU mL⁻¹. Colonies were counted after incubation of 24–48 h at 37 °C. Bacterial regrowth was tested after 24 and 48 h post-treatment, finding that the colonies account was still below the DL in all the cases.

2.3. Water matrixes

Two types of water matrixes were used. Isotonic water (IW), demineralised water with 0.9% of NaCl, to prevent microorganisms' osmotic stress. IW was used for blank experiments, to prevent the influence of any chemical compound. Synthetic rain water (SRW) was proposed as an adaptation from elsewhere [23]. The chemical composition is made of, NaCl (56.1 mg L⁻¹), K₂SO₄ (17.4 mg L⁻¹), CaCl₂ (5.55 mg L⁻¹), MgCl₂ (5.71 mg L⁻¹), NH₄NO₃ (12 mg L⁻¹), KH₂PO₄ (0.14 mg L⁻¹) and CaSO₄·2H₂O (19.7 mg L⁻¹). The main physico-chemical parameters of both water matrixes are shown in Table 2.

2.4. Solar disinfection experiments

Solar experiments were carried out at Plataforma Solar de Almería (South East of Spain). They were done simultaneously in both reactors under real sunny-outdoor conditions for up to 300 min (5 h) (10:30 to 15:30 local time). 10 mL-water samples were taken regularly at pre-determined times. All the experiments were carried out in completely sunny days from March to November 2018. The solar-UVA irradiance ranged from 20 to 53 W m⁻² and water temperature from 15 to 37 °C.

The efficiency of each type of collector (CPC and V-trough mirror) was evaluated in two experimental conditions: i) static batch and ii) recirculated batch. Each condition was evaluated at least in triplicate. The ANOVA analysis of the bacterial count permitted to discard any results

Table 2
Chemical characterisation of the water matrices used in this work.

	Isotonic water	Synthetic rain water
pH	7.06 ± 0.01	5.32 ± 0.01
Conductivity (μS cm ⁻²)	16260 ± 1	261 ± 1
Turbidity (NTU)	< 0.5	< 0.5
Total Organic Carbon (mg L ⁻¹)	< 0.1	< 0.1
Anions (mg L ⁻¹)		
Cl ⁻	5.46 ± 0.01	41.53 ± 0.23
NO ₃ ⁻	–	9.15 ± 0.06
SO ₄ ²⁻	–	21.15 ± 0.25
Cations (mg L ⁻¹)		
Na ⁺	3.54 ± 0.01	23.54 ± 2.15
NH ₄ ⁺	–	2.93 ± 0.27
K ⁺	–	7.82 ± 0.12
Mg ²⁺	–	1.42 ± 0.09
Ca ²⁺	–	6.98 ± 0.09

(–) means non-detectable.

with a confidence level below 95%. The error bar was calculated as the standard deviation of all results. When necessary, additional experiments were carried out under the same conditions to ensure this level of confidence.

The second part of this experimental research consisted on the assessment of the amount of water that can be treated under natural sunlight. For this purpose, the best operating conditions found out in the initial evaluation were used to treat a number of consecutive batches in one day using both solar photo-reactors and SRW with the subsequent monitoring of the concentration of bacteria in the selected consortium.

The solar-UVA radiation was measured with a pyranometer (Kipp&Zonen CUV-5 (280–400 nm)), which provided data in terms of W m⁻². The bacterial inactivation graphs were plotted against the accumulative solar-UVA dose (kJ m⁻²) during the solar exposure period of each sample according to equation (1).

$$Dose_{UV} (J m^{-2}) = \sum_n UV_{n-1} (W m^{-2}) \cdot \Delta t_{n-1} (s) \quad (1)$$

where UV is the average value of UVA radiation received, and Δt is the amount of time the reactor is exposed to solar radiation.

2.5. Actinometrical analysis

Ferrioxalate actinometry was done to determine the photon flux entering into the reactors when they are exposure to natural sunlight. The protocol of the ferrioxalate actinometry is described elsewhere [24]. Briefly, a 6 mmol L⁻¹ solution of Fe (III) was prepared in dark and at pH 3 from Fe₂(SO₄)₃·H₂O. Once the iron was dissolved, oxalic acid was added (30 mmol L⁻¹, from H₂C₂O₄·2H₂O) in the dark to get the formation of the ferrioxalate complex. Afterward, the solution was directly diluted in the reactor water, and then exposed to sunlight. The samples were taken every minute for 15 min. During that period the complete conversion of the Fe (III) to Fe (II) was observed. Iron concentration was measured by a spectrophotometric method as follows: 1 mL of diluted samples (1:10 in MilliQ water at pH 3) was mixed with 7.5 mL of MilliQ water at pH 3 and 1.5 mL of a reactive that consists in 1 g L⁻¹ of 1,10-phenantroline, 0.5 mol L⁻¹ of acetic acid and 1 mol L⁻¹ of sodium acetate. After 10 min in the dark, absorbance was measured at 510 nm that is proportional to the ferrous ion concentration. Iron concentration was then calculated using a standard calibration equation (Fe(II) = 0.020 × Abs (510 nm), R² = 0.999) obtained for the range 0 – 45 mg L⁻¹ of Fe (II).

The actinometrical test was carried out under completely sunny conditions starting at 11:40 a.m. local time, with solar-UVA irradiance of 35 W m⁻² (Fig. S1). Spectral solar irradiance (Fig. S2) was measured from 280 to 600 nm with a spectroradiometer (AvaSpec-ULS2048

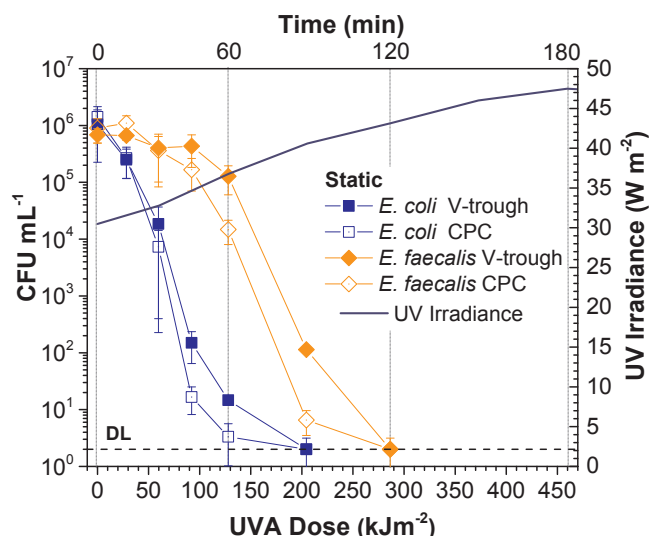


Fig. 2. Solar inactivation of *E. coli* and *E. faecalis* in isotonic water within CPC and V-trough solar reactors in static mode.

Spectrometer, sensitivity of 310,000 counts μW⁻¹ ms⁻¹). The borosilicate transmittance of the photo-reactors was also measured using a spectrophotometer (Evolution, Thermo Fisher Scientific Inc.) (Fig. S3).

3. Results and discussion

3.1. CPC and V-trough reactors for solar *E. coli* and *E. faecalis* inactivation

The disinfection profile of *E. coli* and *E. faecalis* in the CPC and V-trough reactors is shown in Fig. 2. Very similar results were obtained in both reactors under the same conditions. *E. coli* decreased 5.8-LRV from $1.2 \pm 0.77 \times 10^6$ CFU mL⁻¹ to below DL, after 90 min (UVA dose = 204.4 kJ m⁻²). A similar effect was observed for *E. faecalis*, although the required treatment time and dose were higher. This effect is expected for a Gram-positive bacterium due to its thicker cell wall, which has been widely reported to show higher resilient to UV radiation [14]. *E. faecalis* decreased 5.6-LRV in the CPC and 5.7-LRV in the V-trough reactor in 120 min (UVA dose of 286.5 kJ m⁻²) reaching the DL in all cases.

The photon flux received inside both solar photoreactors was estimated by ferrioxalate actinometry. Fe(II) concentration (moles) measured during the test is shown in Fig. 3 (Table S1 and S2). A higher generation rate in CPC ($\alpha = 14.3 (\pm 1.2) \times 10^{-5}$ mol s⁻¹; R² = 0.9) than in V-trough ($\alpha = 8.9 (\pm 0.6) \times 10^{-5}$ mol s⁻¹; R² = 0.9) reactor was observed. The photon flux (q) can be calculated as follows [25,26]:

$$\frac{dN}{dt} = q_{p,0} \sum_{\Delta\lambda} (T_{\lambda i} \phi_{\lambda i} g_{\lambda i} f_{\lambda i}) \quad (2)$$

$$f_{\lambda} = 1 - e^{-k_{\lambda} C_{Fe^{2+}} l} \quad (3)$$

$$q_{p,\lambda} = T_{\lambda} g_{\lambda} q_{p,0} \quad (4)$$

$$q_p = \sum_{\Delta\lambda i} q_{p,\lambda} \quad (5)$$

where, dN/dt is the amount of Fe²⁺ moles generated per time (mol s⁻¹); $q_{p,0}$ is the total incoming photon flux at the surface of the photoreactor (E s⁻¹), q_p is the total photon flux received (E s⁻¹), T_{λ} is the photoreactor's material transmittance (in this case borosilicate, Fig. S3), ϕ_{λ} is the quantum yield of Fe³⁺ (mol E⁻¹), g_{λ} is the density function of the light (sun), f_{λ} is the absorbed fraction of the light, k_{λ} is the Napierian spectral molar absorptivity of Fe³⁺ (cm² mol⁻¹), $C_{Fe^{2+}}$ is the final concentration of Fe²⁺ (mol cm⁻³), and l is the optical path length (cm).

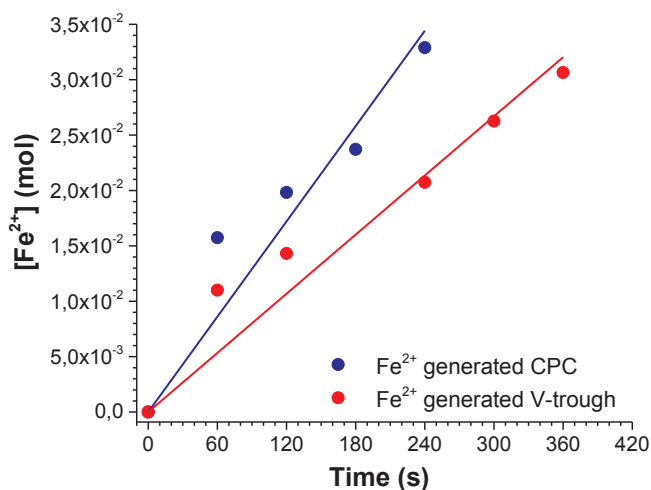


Fig. 3. Fe^{2+} generation for CPC and V-trough reactors during actinometrical test.

With the generated moles of Fe^{2+} measured in both reactors, the data obtained from the literature for ϕ_{λ} and k_{λ} [26] and using the equations 2–5, the photon flux was estimated for both reactors (Table S3). The photon flux (q_p) in the CPC reactor was $3.67 \times 10^{-4} \text{ E s}^{-1}$, which was 1.58 times higher than the fluence in the V-trough reactor, $2.32 \times 10^{-4} \text{ E s}^{-1}$. Using the spectral distribution of the solar radiation measured during the actinometric experiment (Fig. S3), the total solar-UVA irradiance received inside each reactor can be calculated, 65.29 W m^{-2} in the CPC and 40.36 W m^{-2} in the V-trough reactor.

The actinometry results showed that the optical performance of CPC is much better than V-trough reactor, as it was expected since the CPC has a concentration factor (CF) of 1.04 and the V-trough mirror CF is 0.56 (Table 1).

The kinetic analysis of bacterial disinfection shows a shoulder + linear pattern [27] in the case of *E. faecalis* and only a linear kinetic for *E. coli* (Fig. 2). The absence of shoulder in *E. coli* can be attributed to its higher sensitivity to solar disinfection. *E. faecalis* shows shoulder-length values of 15 min (CPC) and 45 min (V-trough). During this lag-phase, there is a disinfection delay of 30 min in the V-trough as compared to the CPC, during this period the *E. faecalis* concentration decreases 1-log more in the CPC than in the V-trough. The linear inactivation phase of each bacterium leads to the following kinetic values (k): $-0.048 \pm 0.006 \text{ min}^{-1}$ ($R^2 = 0.9$) and $-0.041 \pm 0.004 \text{ min}^{-1}$ ($R^2 = 0.99$) for *E. coli* in the CPC and V-trough reactor, respectively. While, for *E. faecalis* these values were $-0.030 \pm 0.005 \text{ min}^{-1}$ ($R^2 = 0.99$) and $-0.029 \pm 0.003 \text{ min}^{-1}$ ($R^2 = 0.9$) in the CPC and V-trough reactor, respectively. According to the actinometrical results, we might expect a faster inactivation in the CPC, nevertheless, only *E. coli* shows a 15% faster inactivation kinetics. At the same time, no differences between both reactors are spotted for *E. faecalis* in the linear phase, while lag-phase in *E. faecalis* shows the enhancement of the CPC by the higher received radiation. Notwithstanding, the similar kinetic values of both reactors can be attributed to the UV-dose response of bacteria to solar exposure, where once delivered the lethal dose required for each species, the extra radiation dose doesn't make a measurable difference in the kinetics [16]. We must also consider that SODIS mechanism is explained by a combination of endogenous and exogenous sub-lethal damaging effects consequence of solar UVA and very little UVB radiation [28]. When radiation acts over the bacteria, the solar UVB fraction affects mainly to cell DNA and other cellular targets including some proteins and enzymes by the direct light absorption of endogenous chromophores. The solar UVA fraction also damages the DNA and cellular compounds indirectly, through reactions with other molecules including photosensitisers, which leads to the

increment of internal reactive oxygen species (ROS) [28,29]. The main ROS formed inside cells are free radicals and includes hydroxyl (HO^\bullet), superoxide ($\text{O}_2^{\bullet-}$), hydroperoxyl (HO_2^\bullet), peroxy (ROO^\bullet), alkoxyl (RO^\bullet), as well as other non-radical species like hydrogen peroxide (H_2O_2), singlet oxygen ($^1\text{O}_2$), and hypochlorous acid (HOCl) [28]. All these oxidative species initiate a chain of oxidative reactions that bacteria are not able to overcome. These damaging effects take time to be accumulated and showing their detrimental results on bacterial survival [11]. This would explain why the kinetics of both bacteria are very similar in both reactors.

Previous research has reported similar lethal solar-UVA dose to reduce 6-log of *E. coli* K12 by solar disinfection in different CPC reactors in static batch mode, such as 108 kJ m^{-2} in well water using 2.5 L-CPC (area of 0.21 m^2) with borosilicate glass tube of 50 mm diameter [16]; $180 \pm 20 \text{ kJ m}^{-2}$ in well water using 25L-CPC with a photo-reactor tube of 200 mm diameter [17], which is very close to the value obtained in this work for the inactivation of *E. coli* K12 in both mirror configurations (201.6 kJ m^{-2}) but for higher treated volumes, 32 and 54 L for CPC and V-trough reactors, respectively.

3.2. Effect of water recirculation on bacterial solar inactivation

To treat all the water in the system, including the 6 and 7% of the dead volume in the CPC and V-trough reactors, the disinfection performance at the lowest flow rate possible, 2 L min^{-1} , was tested (Fig. 4). A significant difference between the disinfection profiles of both bacteria was found in static and recirculation modes. The *E. coli* concentration decreased 5.6-LRV, from $8.7 \pm 2 \times 10^5 \text{ CFU mL}^{-1}$ to below DL, in 300 min of solar treatment time, with a solar-UVA dose of 775.3 kJ m^{-2} , which is ca. 4 times more solar-UVA dose due to recirculation than the required in static mode, 204.4 kJ m^{-2} . Similarly, *E. faecalis* under recirculation registered a 4.7-LRV, from $8 \pm 2.5 \times 10^5 \text{ CFU mL}^{-1}$ to $18 \pm 5 \text{ CFU mL}^{-1}$ in the CPC, and a 5.0-LRV, from $7 \pm 2.5 \times 10^5 \text{ CFU mL}^{-1}$ to $7 \pm 4 \text{ CFU mL}^{-1}$ in V-trough reactor, with a total received UVA dose of 775.3 kJ m^{-2} , this is 2.7 times higher dose than in static mode, 286.5 kJ m^{-2} .

The need for flowing water volumes when large scale systems are used is clear. For this reason, studies to determine the effect of low flow conditions ($< 2 \text{ L min}^{-1}$) on the disinfection performance were done as a design limiting factor. Nevertheless, our results clearly demonstrated a better inactivation results under static conditions, which agree with other studies in literature [17,20]. Previous research showed that recirculation of water in a solar disinfection system plays a negative role in the disinfection efficiency [16], as bacteria will recover from solar damage and create resistance to solar inactivation [28], which would explain the results of the present work.

3.3. Daily treatment capacity

To evaluate the amount of water that can be treated in one typical sunny day, consecutive solar tests in the static mode were performed in the CPC and V-trough reactors. Fig. 5 shows the inactivation results of three consecutive runs of 80 min exposure each at different local times. Each run treated 32 L for the CPC and 54 L for V-trough reactor. The first run carried out from 10:15 to 11:35 am, received 144 kJ m^{-2} of solar-UVA and reduced 6-LRV of *E. coli* while *E. faecalis* attained 3-LRV for both reactor types. The second (12:05 to 13:25 pm) and third (13:55 to 15:15 pm) runs resulted in complete inactivation (below DL) of both bacteria in the two reactors with solar-UVA dose values of 216 kJ m^{-2} and 234 kJ m^{-2} , respectively.

The first run received a 40% less of UVA dose than the other runs, this is why we observed a partial removal of *E. faecalis*, while *E. coli* achieved the DL in all cases, as it is more susceptible to solar radiation. Although both solar reactor types showed same disinfection performance, they treat different water volumes, 32 L run⁻¹ in the CPC and 54 L run⁻¹ in the V-trough. Therefore, up to 96 L of SRW can be treated

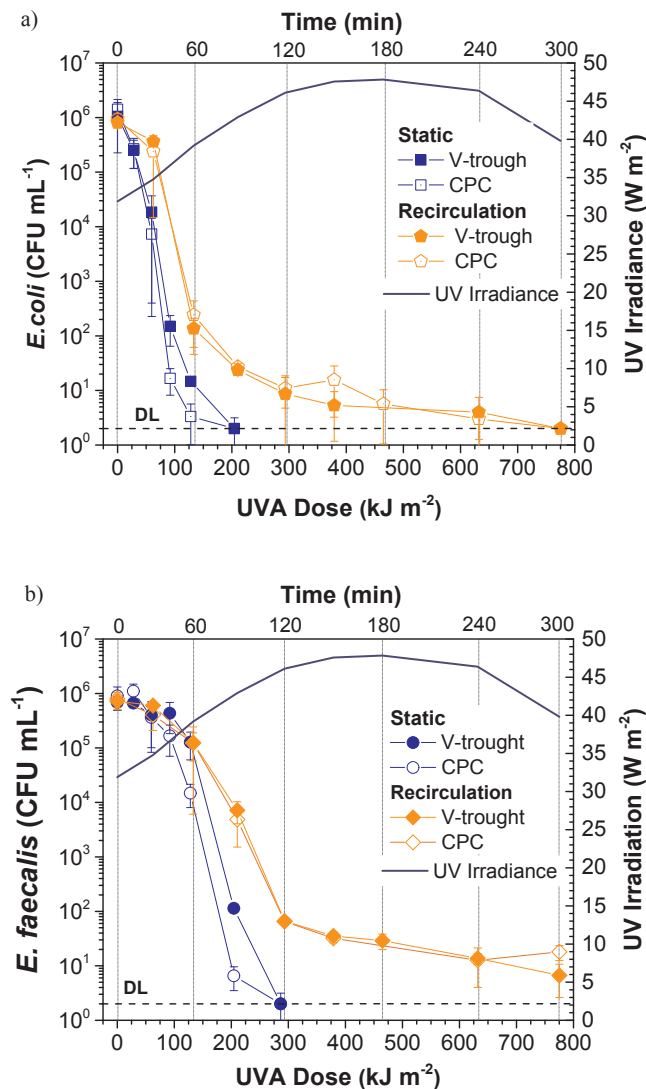


Fig. 4. Solar inactivation of *E. coli* (a) and *E. faecalis* (b) in isotonic water within CPC and V-trough solar reactors in recirculation and static modes.

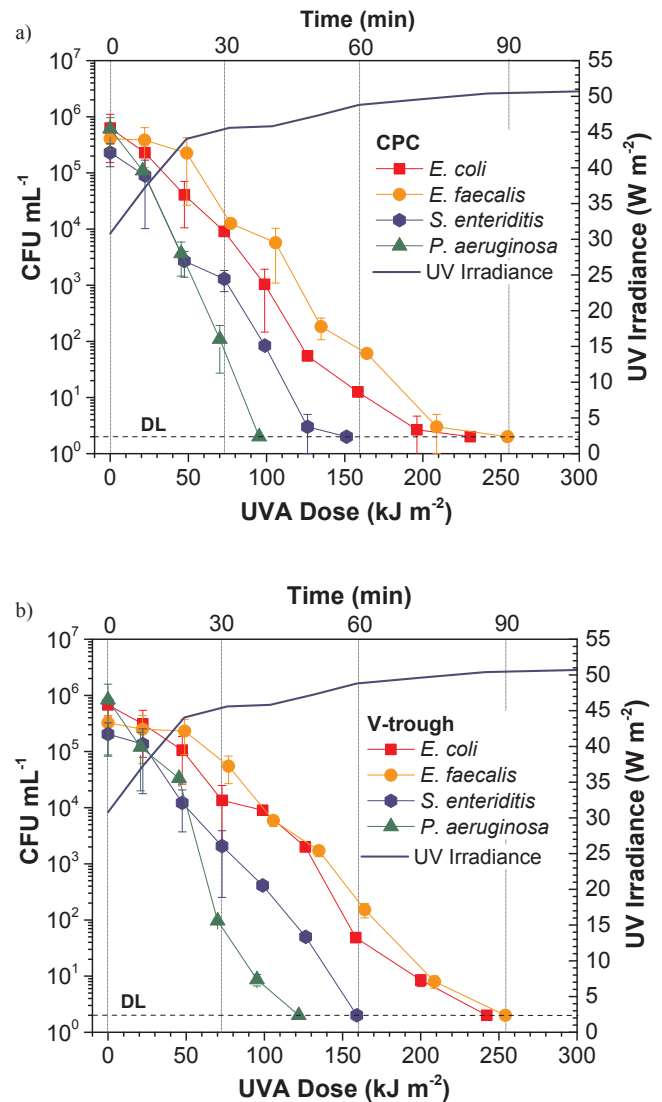


Fig. 6. Inactivation rates of *E. coli*, *E. faecalis*, *S. enteritidis* and *P. aeruginosa* in SRW and static mode in a) CPC and b) V-trough solar reactor.

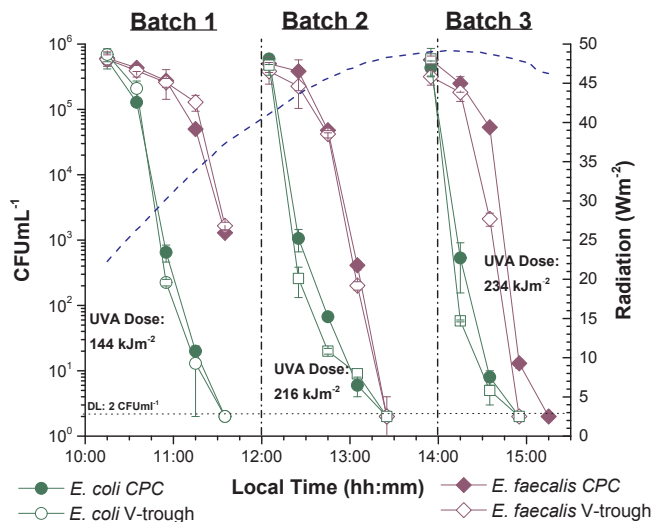


Fig. 5. Inactivation of *E. coli* and *E. faecalis* with SRW during one day in V-trough and CPC-reactor in static mode.

with the CPC and 162 L in the V-trough under natural sunlight, when at least 200 kJ m^{-2} of solar-UVA dose per run is delivered in the system.

3.4. CPC and V-trough reactors for solar inactivation of a bacterial consortium

The selected consortium of bacteria was used to test the disinfection efficacy of the solar reactors with synthetic harvested rainwater (Fig. 6). The performance of CPC and V-trough systems was similar. The order of sensitivity to solar radiation of these bacteria was found to be: *P. aeruginosa* > *S. enteritidis* > *E. coli* > *E. faecalis*.

In the CPC reactor, the results showed 5.5-LRV of *P. aeruginosa* concentration ($6.1 \pm 3.5 \times 10^5 \text{ CFU mL}^{-1}$ to DL) with 95.2 kJ m^{-2} UVA dose (40 min – solar exposure); *S. enteritidis* viable counts decreased 5.1-LRV ($2.3 \pm 1 \times 10^5 \text{ CFU mL}^{-1}$ to DL) with 151.2 kJ m^{-2} UVA dose (around 60 min – solar exposure); *E. coli* concentration diminished 5.5-LRV ($6.3.0 \pm 4.7 \times 10^5 \text{ CFU mL}^{-1}$ to DL) after receiving a solar-UVA dose of 239.4 kJ m^{-2} ($\approx 90 \text{ min}$ – solar exposure); and finally, *E. faecalis* concentration was reduced 5.3-LRV ($4.1 \pm 0.8 \times 10^5 \text{ CFU mL}^{-1}$ to DL) after receiving a solar-UVA dose of 254.1 kJ m^{-2} (90 min – solar exposure). In the V-trough system, the results were very close to the CPC ones.

Other authors showed similar resistance of these bacteria to solar disinfection [30]. They found that *P. aeruginosa* had a higher sensitivity to UVA radiation (365 nm) than *E. coli*. In this study, *P. aeruginosa* had a survival rate of 20% instead of the almost 100% of *E. coli* exposed to 120 kJ m⁻².

3.5. Feasibility and economic assessment of the solar reactors

To select a technology for drinking water at a household level, four main aspects must be considered in the following order of priority, the disinfection efficiency, the amount of water delivered, economic affordability and adaptation to the local context [2,31]. The first criterion is crucial and requires assessing the technology according to the harmonised protocol of the WHO for Household Water Treatment and Safe Storage (HWTS) [31]. *E. coli* is established as a bacterial indicator in this scheme, with the highest protection level (so-called 'highly protective') when a 5-LRV is achieved. Our results showed that such level of protection is achieved for *E. coli* and the most frequently found pathogens in harvested rainwater in all the evaluated cases, i.e. for IW and SRW, CPC and V-trough reactors.

Other biological indicators of the HWTS testing protocol include MS2 (bacteriophage) and *Cryptosporidium parvum*. It would be desirable to investigate the disinfection efficiency of the solar V-trough reactor with these indicators and even to validate the performance in the field under real conditions of sunlight and real harvested rainwater, although this research is the object of other articles [32].

Regarding the amount of treated water daily, the United Nations (UN) has established the recommended minimum drinking water needs, which vary from 20 to 50 L person⁻¹ day⁻¹ [33]. The V-trough reactor has been proven to be able to provide 162 L of treated rainwater on a sunny day.

The design of this reactor is made so it is nearly user-independent, as it only requires to clean it (outside parts), fill it (pipe of hose connected to the rainwater tank) and track the time of solar exposure for up to 100 min regardless of the local time and the weather, except for cloudy or rainy days. Also, this reactor design accomplishes the requirement of permitting an accessible and affordable water resource, which according to WHO [34], it must be within 1,000 m of the home or < 30 min' collection time.

Finally, the water costs might not exceed 3% of the household income according to the UN [33]. Our results showed a similar disinfection performance of the CPC and V-trough reactors for the evaluated SRW. However, the V-trough reactor can treat 66% more volume of water for the same surface area. Moreover, the manufacturing cost of the CPC reactor is 50% higher than V-trough cost (data provided by Ecosystem Services, S.A.). Therefore, the use of a V-trough system would reduce the total cost of the treated water significantly as compared to the CPC.

According to the manufacturer, the fabrication cost of this V-trough reactor is 900 US\$ with no maintenance costs as the system is gravity fed and only needs routine cleaning. Considering the life-span of the system of 10 years, an average treatment capacity of 150 L per day, and an average of 2,300 – 2,500 h of sun or 300 sunny days per year in the area [35], a cost of US\$ 0.2 per 100 L of treated water is estimated. This compares favourably with commonly used point-of-use water treatment processes, such as chlorine solutions and P&G PUR® sachets, which have been estimated to cost \$0.045 and \$1.00 per 100 L, respectively [36]. In addition, this solar process avoids the use of chlorine, which can generate organic intermediates if there is organic matter dissolved in the collected water. If the system is implemented in areas, like schools, small villages, or local clinics, the benefits of a shared-use will improve the health of the community through improved water quality. This will also have positive effects in their wellbeing, the school attendance of children and more time to work in other profitable activities for mothers, as they usually take the responsibility of water in the domestic environment.

4. Conclusions

A new V-trough solar disinfection reactor has been designed, constructed and tested to improve the biological quality of harvested rainwater in sunny and isolated areas of low-income countries. This reactor has a treatment capacity of 162 L per day (sunny day, with at least 300 min of clear sunshine).

The assessment of the disinfection performance of the V-trough reactor under controlled conditions (synthetic rainwater and spiked selected consortium of bacteria) showed that > 5-LRV of *P. aeruginosa*, *S. enteritidis*, *E. coli* and *E. faecalis* (in order of sensitivity to the treatment) was achieved in a range between 40 min and 90 min or a solar-UVA dose between 130 and 250 kJ m⁻². The best disinfection results were obtained when the reactor is used in static mode (no water recirculation).

Despite the almost 1.6 times higher photon flux of the CPC against the V-trough -confirmed by actinometrical measurements- the response of the bacteria to the solar treatment did not show any significant difference in the kinetics among both reactors.

The comparison between the V-trough and CPC reactor showed that the efficiency for water disinfection is similar for all the pathogens evaluated. Moreover, the V-trough can treat 54 L and the CPC 32 L per module of 2 m². Therefore, the V-trough reactor offers a clear advantage in terms of cost per volume of treated water (US\$ 0.2 per 100L).

The V-trough reactor offers the possibility of delivering safer drinking water to communities with high solar irradiance and lack of access to improved water sources. This is due to the low cost of the treated water, high performance, long life-span (10 years), and low maintenance (cleaning only), without chemicals or electricity needs.

Further studies on the social acceptance of this technology in rural communities of Uganda and South Africa are being carried out under the WATERSPOUTT project.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cej.2020.125719>.

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